

GENETIC REGULARITIES OF THE CHEMICAL COMPOSITION AND CERTAIN
CHARACTERISTICS OF THE STRUCTURE AND ORIGIN OF METEORITES

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CHARACTERISTICS OF THE STRUCTURE AND ORIGIN OF METEORITESA. A. Yavnel¹

ABSTRACT. The results of an analysis of the chemical composition of meteorites are discussed. Regularities are shown to exist which are reflected in the relationship of the percentage of the metal in the meteorite to the percentage of nickel in the metal when the data are analyzed for the types of meteorites, including achondrites, chondrites, mesosiderites, pallasites and siderites. Conclusions are reached that meteorite material was differentiated by chemical composition during various evolutionary stages and that meteorites were formed from small bodies in which the primary structural features were established.

In solving the problem of the origin of meteorites, an important part is /139* played by the study of their matter, particularly chemical composition and structure. Meteoritic matter consists mainly of two phases: the silicate and the metallic. The silicate phase is composed of minerals which are mainly magnesium silicates. The metallic phase is a solid solution of nickel in iron with the addition of cobalt and other elements. In addition to these two components phases are also present in meteorites which belong to other mineral classes. The most abundant of these is troilite-iron sulfide.

Depending on the ratio between the silicate and metallic phases, meteorites are divided into three classes: the stony, stony-iron and iron meteorites. Among these classes the author [1] isolates the following sub classes, arranged in decreasing order of the silicate phase: calcium-rich achondrites; calcium-poor achondrites; chondrites; mesosiderites; pallasites; and siderites. Meteorites of these sub classes differ from each other in composition and structure. Significant variations in chemical composition are also observed within each sub class. Previous investigations by Prior [2] have established that in chondrites the FeO content is increased in the silicate phase and simultaneously the metallic phase content decreases; as a result the nickel content in the metal increases.

*Numbers in the margin indicate pagination in the foreign text.

Urey and Craig [3] divide chondrites into two groups according to the total content of iron in them.

During the investigation of this problem the author [4,5] used the most reliable results of the analysis of meteorites of all classes. In order to make it possible to compare the basic composition of meteorites, selected as characteristic were FeO in the silicate phase, Ni in the metallic phase and nickel-iron. Specifically this permitted us to compare the composition of iron meteorites and the metallic phase of stony and stony-iron meteorites.

The results of the processing of analytical data are shown in the form of bar graphs. For iron meteorites based on an analysis of over 400 meteorites, naturally only a bar graph of the nickel content has been plotted (see Figure 1).

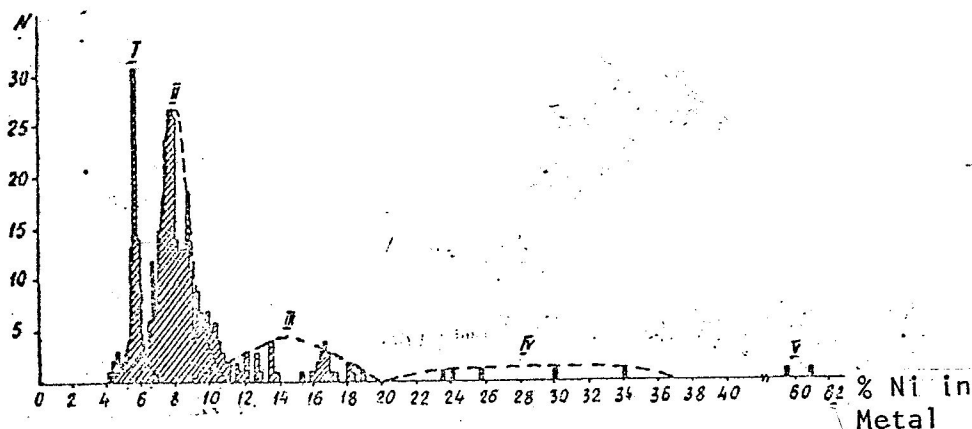


Figure 1. Distribution of Iron Meteorites by Nickel Content.

It is obvious that the distribution of iron meteorites by nickel concentration has a complex nature. A sharp maximum is isolated on the graph with 5.6% Ni, a maximum at approximately 8% Ni, as well as a group of meteorites with an average content of approximately 14% Ni, and a maximum in the region 20-40% Ni near 60% Ni. The presence of several groups of iron meteorites indicates, first of all, that their crystallization could not have occurred in one mass, for example, in the center of a single parent planet. Even if we assume the liquation of an original iron-nickel melt during solidification, it would lead only to a continuous change in its composition.

/140

We shall examine the composition of chondrites, which represent the most abundant type of meteorites. Bar graphs of the composition and phase relationship of chondrites, compiled from the results of the analysis of ~100 meteorites demonstrate the division of chondrites into groups according to nickel-iron content, Ni in the metallic phase and FeO in the silicate phase (see Figure 2). Group I of the chondrites--enstatite chondrites--contain an insignificant quantity of FeO in silicate minerals and a maximum in the metallic phase. Groups II and III chondrites are more clearly distinguished by the quantity of nickel-iron, while Group IV is distinguished by Ni in the metallic phase. In addition, in a group of chondrites (carbonaceous chondrites) there is practically no nickel-iron. If we turn our attention to the metallic phase composition of five groups of chondrites, we see that nickel in these amounts on the averages to 6.5, 9, 14, 30 and > 50%. Thus, there is a specific correlation between this composition and nickel content in five groups of iron meteorites.

The results obtained confirmed the relationship between composition and the number of phases in chondrites--the so-called Prior rule. However, in contrast to Prior's assumption, it does not have a continuous but a discrete nature, as a result of which we have termed it the Prior "group" rule.

A similar examination of the composition of stony-iron meteorites, including pallasites and mesosiderites was based on a small number of available analyses, which resulted in tentative conclusions only. On the pallasite composition bar graph (see Figure 3) it is possible to distinguish their separation by selected indicators into two groups. In one group there is 5.5-12% Ni in nickel-iron, which corresponds to Group II of iron meteorites. According to nickel-iron composition (13-17% Ni) another group of pallasites is close to Group III of the iron meteorites. Further, it can be seen from the data obtained that in pallasites a regular relationship is seen between the quantity and composition of nickel-iron and the FeO content in the silicate phase, /141
similar to the Prior Group rule in chondrites.

In analyzing the bar graph of the composition of mesosiderites (see Figure 4), it may be assumed that the main mass of meteorites of this type fall into one group. Judging by the nickel content in the metallic phase, it is much more likely that they correspond to Group II of iron meteorites. An exception

is the Benkubbin mesosiderite which stands out from the total number by its reduced FeO content in nickel silicate (5.8%) in metal, which is characteristic for Group I iron meteorites.

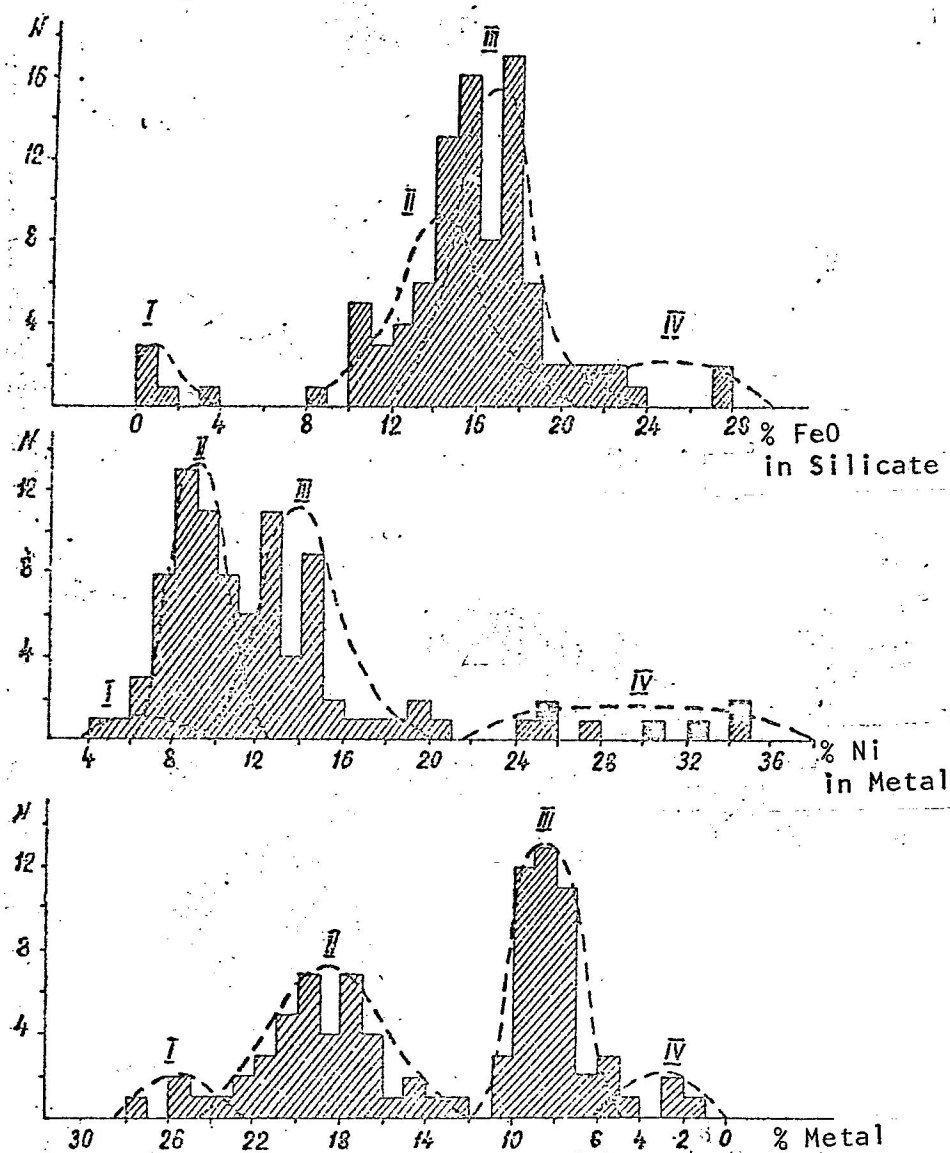


Figure 2. The Distribution of Chondrites by Content of FeO, Nickel and Metal.

The bar graphs of the composition of a few sub classes of achondrites with an insignificant quantity of nickel-iron characterize the content of main elements in the silicate phase. Here we also note the division of achondrites into groups. Calcium-poor achondrites may be combined into five

groups, depending on SiO_2 , MgO and FeO content (see Figure 5). Therefore, in orbits there is nickel-iron with a concentration of 5.6% Ni, which corresponds to Group I of iron meteorites, and 27-33% Ni in amphoterites, which corresponds to Group IV.

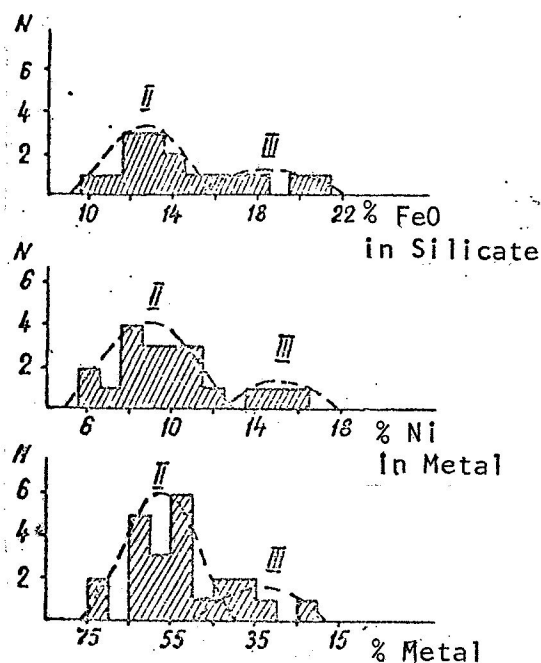


Figure 3. The Distribution of Pallasites by Content of FeO , Nickel and Metal.

Calcium-rich achondrites are also divided into several groups by SiO_2 , MgO , FeO , Al_2O_3 and CaO , however, (since the quantity of diffused nickel-iron in them is insignificantly small) there are no data concerning the quantity of nickel in them (see Figure 6).

Thus, a specific relationship exists between different types of meteorites which can be traced quite clearly due to the presence in them of nickel-iron. On the one hand, a change in the quantity of nickel-iron in meteorites designates a transition from stoney meteorites to iron meteorites through intermediate forms. If

we compare the nickel-iron composition (by nickel content) in different types of meteorites, their genetic relationship appears even more clearly.

Therefore, the relationship between the different types of meteorites is shown on a graph where the percent of nickel-iron in the meteorite is shown on the ordinate and the percentage of nickel in the metallic phase (see Figure 7) is shown along the abscissa. The regularity can be seen in the graph in the relationship between the quantity and the composition of nickel iron in chondrites and stony-iron meteorites. The ratio of the number of iron meteorites to the number of chondrites of corresponding groups also decreases regularly during the transition from Group I to Group V [6]. The direct connection of the metallic phase of stony and stony-iron meteorites with iron meteorites definitely indicates their common origin.

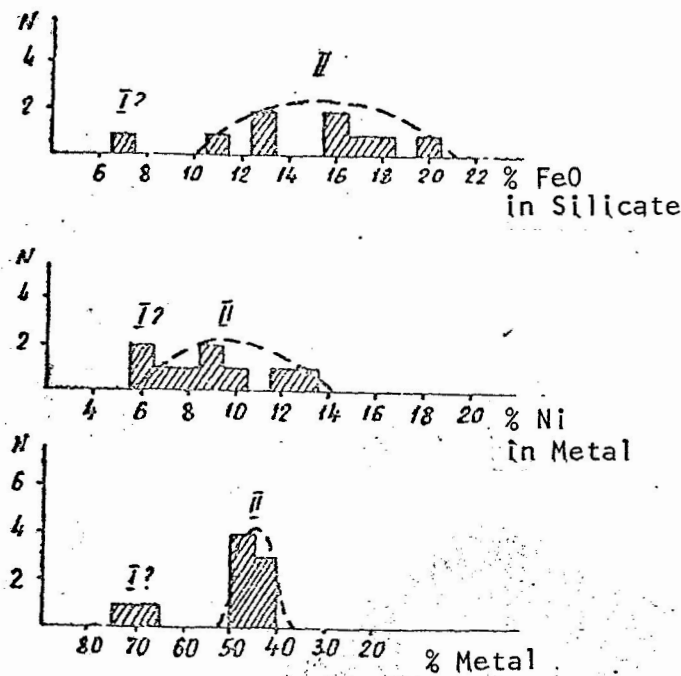


Figure 4. The Distribution of Mesosiderites by FeO, Nickel and Metal Content.

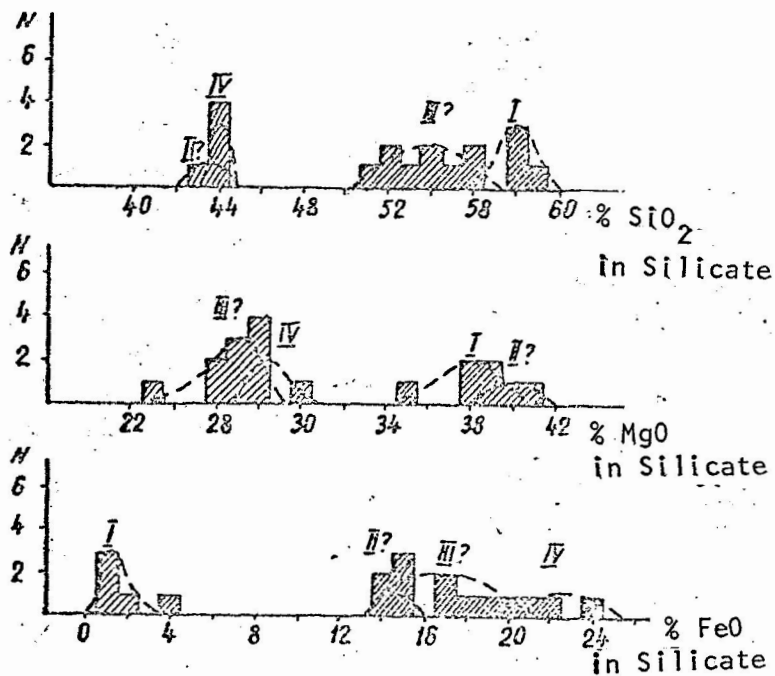


Figure 5. The Distribution of Calcium-Poor Achondrites by SiO₂, MgO and FeO Content.

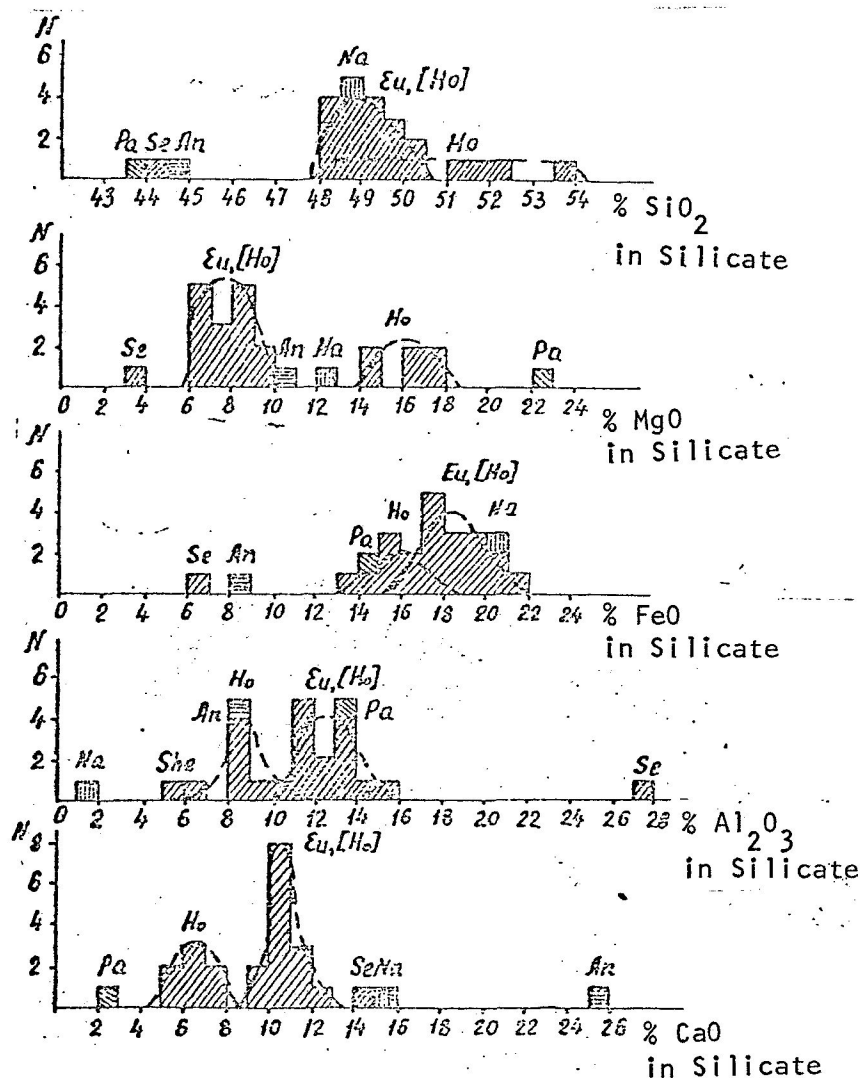


Figure 6. The Distribution of Calcium-Rich Achondrites by SiO₂, MgO, FeO, Al₂O₃ and CaO Content.

Finally, the close genetic relationship of stony and iron meteorites of a given group is also indicated by the change in the degree of thermo metamorphism of their structure. Both in stones (chondrites) as well as in irons the maximum degree of thermo metamorphism of structure, reflected in the recrystallization of matter, is possessed by meteorites in Group I. During the transition to subsequent groups both the number of recrystallized meteorites as well as the temperature of their repeated heating decreases regularly. Therefore the matter of meteorites was heated to the point where the meteorites became individual masses, released from larger bodies.

A subsequent study of regularities in the distribution of the chemical composition of meteorites reveals that the processes of differentiation of meteoritic matter which reflect these regularities were quite complex and probably occurred during various steps in its evolution. This pertains specifically to the composition of chondrites. Having selected as a characteristic of their composition the ratio of the various forms of iron and the atomic ratio of the total iron content to the silicon content, we [7] have plotted a graph (see Figure 8). The axes of the graph show the relative quantities of ferrous iron, metallic iron and iron sulfide. The dashed areas characterized the composition of chondrites and clearly confirm the division of chondrites into groups distinguished by total iron content. Particularly outstanding are Groups II and III, which correspond to two groups of chondrites found by Urey and Craig [3], while the Group I chondrites (enstatites) are divided into two sub groups, and Group V (carbonaceous) is divided into three sub groups. /144

The results obtained show that changes in the total iron content and in the relationships of the different forms in the groups of chondrites are regular. According to these indicators the chondrites in a first approximation may be divided into three sequences or branches. The first branch is made up of enstatite chondrites Ia-Ib; the second branch is made up of bronzite-hypersthene chondrites, II-III-IV; the third group is made up of carbonaceous chondrites, Va-Vb-Vc. /145

Chondrites form the basic mass of meteorites and therefore an explanation of the regularities in their composition has particular significance in characterizing processes which occur during the various stages of the history of meteoritic matter. The different ratio of the total content of iron to silicon most likely indicates occurrences of early differentiation of matter. The reduction in the quantity of ferrous sulfide indicates original sulfur losses which occurred incidently with losses of other volatile components, including water and carbon compounds. A change in the relative content of ferrous iron and metallic iron characterizes different degrees of its oxidation. /146

If we examined the results obtained from this point of view, we shall see that the transition from Groups Vc to Va of carbonaceous chondrites is accompanied by losses of volatile components and by the subsequent reduction of part of the iron oxides. In the Group Va a small loss in sulfur is noted which occurs in parallel with the reduction process. During the transition from Group IV to II of ordinary (bronzite-hypersthene) chondrites, iron reduction is also noted with a certain sulfur loss.

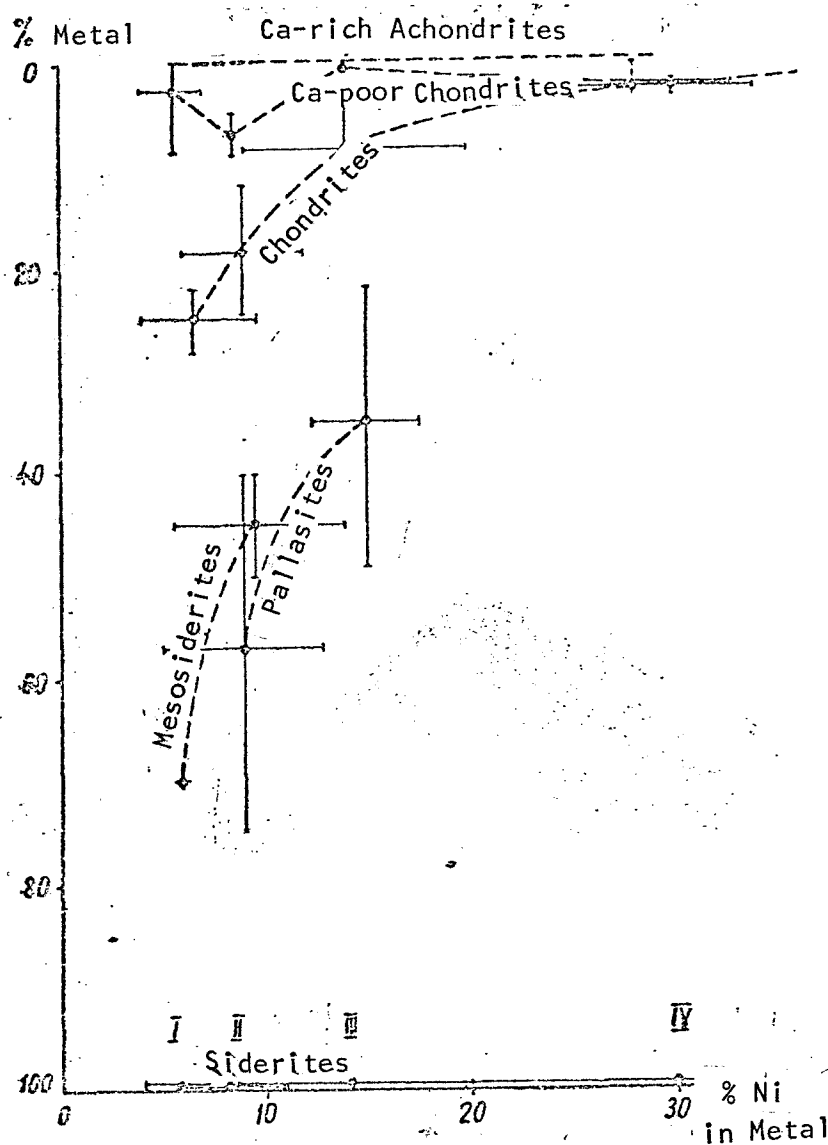


Figure 7. The Relationship Between Ni Content in Metal and the Quantity of Metal in Meteorites of Various Types.

However, the processes of matter differentiation on the one hand and losses of volatile components and iron reduction on the other apparently occurred in opposing directions in carbonaceous and ordinary chondrites. This indicates a different evolution for carbonaceous and ordinary chondrites which must be taken into consideration in establishing a genetic relationship between them.

In order to clarify genetic relationships between the different types of meteorites it is necessary to use data reflecting the content of minor impurities in the isotopic composition of elements. The content of gallium and germanium in nickel-iron meteorites presents a great deal of interest in this regard. As established by Brown and his colleagues [8, 9], iron meteorites may be divided into four groups by gallium and germanium content; these groups do not coincide with the nickel groups, which may indicate different conditions of matter formation. It was shown by the author [10] that the crystallization of iron meteorites of this group also occurred under different conditions. This conclusion is confirmed by the results of an analysis of the structural formation of iron meteorites which represent a nickel-iron alloy with a nickel content which varies within wide limits. In order to explain their phase composition and structure it is necessary to examine the phase diagram of the iron-nickel system which is shown in Figure 9. It is apparent from this figure that phase transformations in nickel-iron occur during its cooling. After crystallization of the alloy from the liquid phase, the γ -phase forms, which is a solid solution of nickel in the face-centered cubic lattice of iron, stable at high temperatures. When the temperature of the initiation of the phase transformation is reached, the α -phase forms in the alloy; this is a solid solution of nickel in the body-centered cubic lattice of iron and the alloy passes to the two-phase region $\alpha + \gamma$. /147

If the alloy contains less than 6% nickel, the transformation $\gamma \rightarrow \alpha$ is fully completed and the alloy consists of the α -phase alone. Since the alloy is cooled slowly the structure of such meteorites is often represented by α -phase crystals which we also observe in so-called hexahedrites. With a higher content of nickel the alloy even at low temperatures remains in the two-phase region. In view of the fact that the formation of the α -phase occurs along the planes of the octahedron of the crystal lattice of the γ -phase, the

structure of similar meteorites, called octahedrites, have the form of α -phase bars, bordered by γ -phase strips and intersecting at appropriate angles.

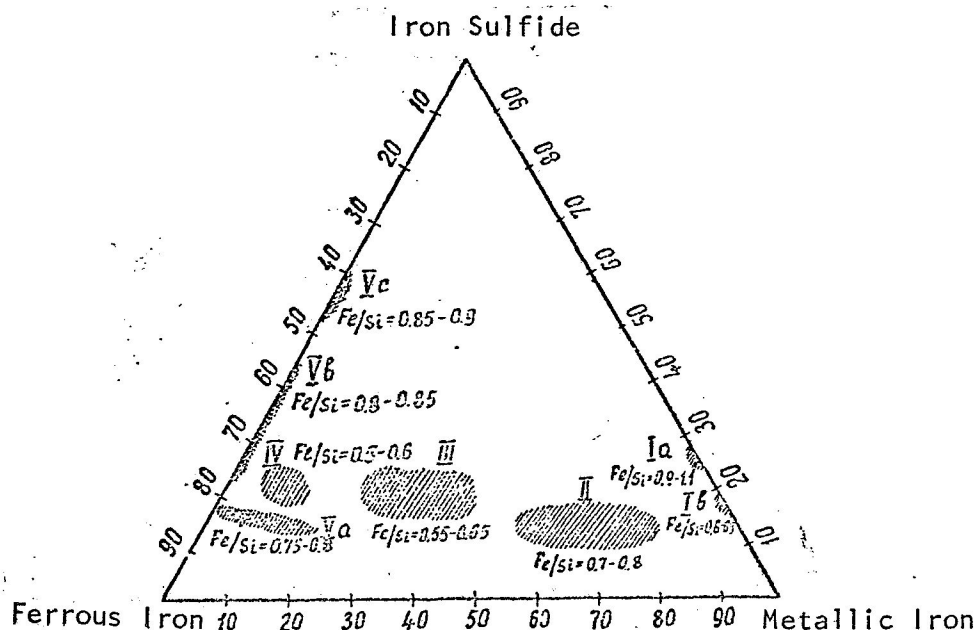


Figure 8. The Relative Quantities of Iron and its Forms and Chondrites.

Since the growth of α -phase crystals is a diffusion process which has a clear dependence on temperature, the width of the bars of this phase decrease with an increase in the nickel content which reduces the $\gamma \rightarrow \alpha$ transformation temperature. The structure of meteorites is affected not only by the influence of the crystallization and recrystallization of the alloy, but also by the nickel-iron composition.

Thus the width of the α -phase bars must decrease with an increase in pressure which reduces the transformation temperature, and with an increase in the alloy cooling rate.

It is apparent from the graph (see Figure 10) that meteorites of individual Ga-Ge groups have a different structural dependence on the nickel content which is explained by the difference in the conditions of their crystallization. A 148 detailed study of the phase composition and structure of iron meteorites allows us the evaluation of these conditions.

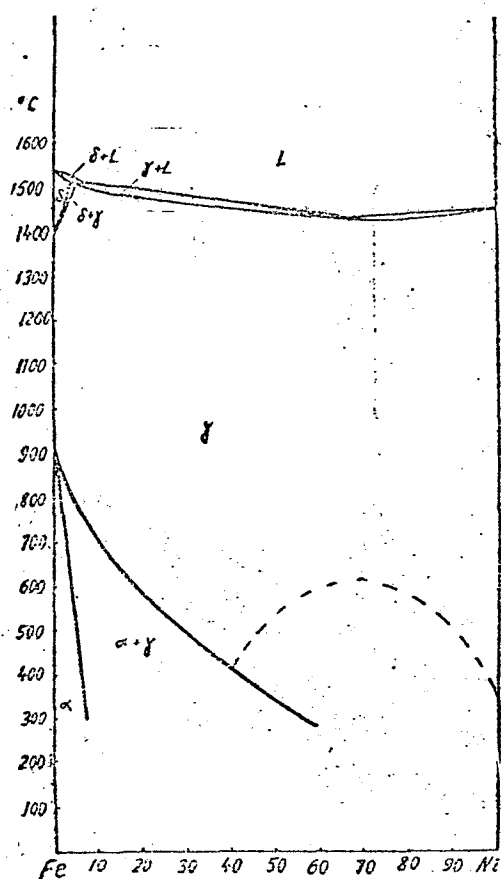


Figure 9. Phase Diagram of the Iron-Nickel System.

First of all it is necessary to determine the pressure at which crystallization occurred. In the opinion of Ringwood and Kaufman [11], judging by the phase diagram of the Fe-Ni system, the phase composition and structure observed in iron meteorites could not form at a pressure above $6 \cdot 10^4$ atm. However, this estimate gives only an upper limit for the pressure value. Therefore in order to determine the pressure, several authors examined the formative conditions in iron meteorites of certain minerals, primarily diamond.

Urey [12], for example, proceeds from the fact that the formation of diamonds in meteors requires the high pressure $\approx 3 \cdot 10^4$ atm and a temperature of $1000-1200^\circ \text{C}$, because he believes that at least one of the parent objects was of lunar dimensions. Anders [13,

14] presents the mechanism of the formation of diamonds in iron meteorites differently. He believes that high pressures are not required; diamonds can form in connection with a shock. A. P. Vinogradov and G. P. Vdovkin [15] believe that diamonds in stony meteorites were formed in carbon matter as a result of internal tensions also in connection with a shock.

At the present time a discussion is being carried on with respect to the conditions of the formation in iron meteorites of another mineral--cohenite (nickel-iron carbide). In the opinion of Ringwood [16, 17] this mineral was preserved in meteorites under the influence of pressures above $2.5 \cdot 10^4$ atm, whereas Lipschutz and Anders [13, 18] maintain that the stability of cohenite is not affected by pressure.

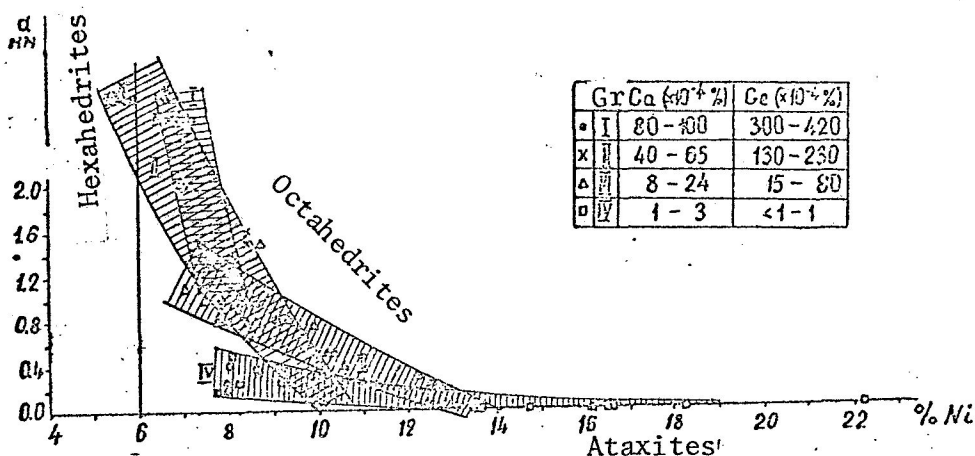


Figure 10. The Structure of Iron Meteorites of Different Ga-Ge Groups As a Function of Nickel Content.

Finally, in a recent work Marvin [19] noted in certain iron meteorites a modification of quartz, or tridymite, which is stable at pressures of not more than 3000 atm. If we accept this pressure estimate at the center of the parent body, the diameter of the latter can not exceed 800 km (the diameter of the asteroid Ceres).

Further, it is possible to determine the time of the structural formation of iron meteorites, based on a study of their phase composition. Investigations which we accomplished [20] by the method of z-ray spectral microanalysis revealed that meteoritic iron is not in an equilibrium state. This is clearly seen (see Figure 11) on the graph which shows the content of the basic elements Fe, Ni, Co and the α - and γ -phases of the Chebankol octahedrite. If the nickel concentration in the γ -phase at the boundary with the α -phase equals 42%, within the γ -phase band the fixed concentration amounts to only 20% Ni. It follows from this that the minimum equilibrium temperature attained by the alloy was approximately 600° C. Our results were confirmed by other authors [21, 22, 23]. Massalski and Park [24] calculated that the time interval for the formation of the structure of iron meteorites in a body with a diameter of 200-400 km is of the order of 10^7 - 10^8 years. This time interval agrees with the results of an approximation of the rate of growth of phosphides in iron meteorites [25], which may serve as indirect confirmation of the estimate of parent body dimensions.

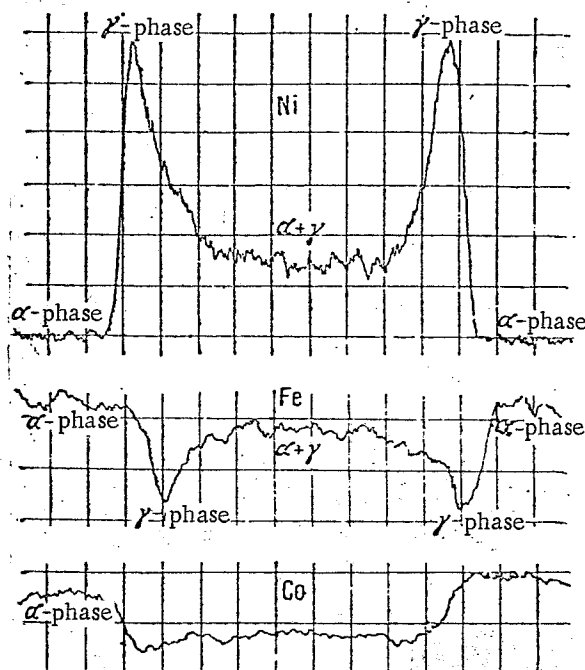


Figure 11. The Distribution of Nickel, Iron and Cobalt in the γ -Phase with the Inclusion of a Finely Divided $\alpha + \gamma$ Mixture.

In this short survey we did not touch upon questions associated with the structural formation of stony meteorites, including the question of the origin of chondrites. In this connection it is possible to indicate only that at the present time various points of view exist regarding the origin of chondrites and these can be divided basically into three groups: 1) condensation from a gas cloud; 2) spraying of drops in connection with the collision of planetoids; 3) volcanic action on parent bodies. In favor of the hypothesis of the prior formation of chondrites is the recent work of Merrihue [26] in particular, which concerns the excess of the xenon 129 isotope in chondrites of the Bruderheim meteorite.

CONCLUSIONS

1. At various stages in the evolution of meteoritic matter, its differentiation by chemical composition occurred which must be considered in dividing meteorites into groups depending on chemical properties. /150
2. Meteorites were formed from several parent bodies probably of asteroidal dimensions, in which the basic features of their internal structure were ultimately formed.

REFERENCES

1. Yavnel', A. A., *Meteoritika*, No. 15, p. 115., 1958.
2. Prior, G. T., *Mineral Mag.*, No. 18, p. 26, 1916.
3. Urey, H. C. and H. Craig., *Geochim. et cosmochim. acta*, Vol. 4, No. 1/2, p. 36, 1953.
4. Yavnel', A. A., *Doklady AN SSSR*, Vol. 102, No. 3, p. 477, 1955.
5. Yavnel', A. A., *Geokhimiya*, Vol. 2, No. 78, 1956.
6. Yavnel', A. A., *Astron. Zh.*, Vol. 3, No. 34, p. 445, 1957.
7. Yavnel', A. A., *Meteoritika*, Vol. 36, No. 23, 1963.
8. Goldberg, E., A. Uchijama, and H. Brown, *Geochim. et cosmochim. acta*, Vol. 2, No. 1, p. 1, 1951.
9. Lovering, J. R., W. Nichiporuk, A. Chodos, and H. Brown, *Geochim. et cosmochim. acta*, Vol. 4, No. 11, p. 263, 1967.
10. Yavnel', A. A., *Meteoritika*, No. 20, p. 114, 1961.
11. Ringwood, A. E., and L. Kaufman, *Geochim. et cosmochim. acta*, Vol. 10, No. 26, p. 999, 1962.
12. Urey, H. C., *Astrophys. J.*, Vol. 3, No. 124, p. 623, 1956.
13. Lipschuta, M. E. and E. Anders, *Geochim. et cosmochim. acta*, Vol. 24, No. 1/2, p. 83, 1961.
14. Anders, E., *Astrophys. J.*, Vol. 134, No. 3, p. 1006, 1961.
15. Vinogradov, A. P. and G. P. Vdovkin, *Geokhimiya*, Vol. 8, p. 715, 1963.
16. Ringwood, A. E., *Geochim. et cosmochim. acta*, Vol. 20, No. 2, p. 155, 1960.
17. Ringwood, A. E. and M. Seabrook, *Geochim. et cosmochim. acta*, Vol. 4, No. 26, p. 507, 1962.
18. Lipschutz, M. E. and E. Anders, *Geochim. et cosmochim. acta*, Vol. 196, No. 634, p. 4855, 1962.
19. Marcin, U. B., *Nature*, Vol. 196, No. 634, p. 4855, 1962.
20. Yavnel', A. A., I. B. Borovskiy, N. P. Il'in, and I. D. Marchukova, *Doklady AN SSSR*, Vol. 123, No. 2, p. 256, 1958.
21. Maringer, R. E., N. A. Richard, and A. E. Austin, *Trans. Metallurg. Soc., A.I.M.E.*, Vol. 1, No. 215, p. 56, 1959.
22. Feller-Kniepmeier, M. and H. H. Uhlig, *Geochim. et cosmochim. acta*, Vol. 21, No. 3/4, p. 257, 1961.
23. Agrell, S. O., J. V. P. Long and R. E. Ogilvie, *Nature*, Vol. 198, No. 749, p. 4882, 1963.
24. Massalski, T. B. and F. R. Park, *J. Geophys. Res.*, Vol. 7, No. 67, p. 2925, 1962.
25. Goldstein, J. I. and R. E. Ogilvie, *Geochim. et cosmochim. acta*, Vol. 27, No. 6, p. 623, 1963.
26. Merrihue, C. M., *J. Geophys. Res.*, Vol. 1, No. 68, p. 325, 1962.

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